IN-LINE OIL DEBRIS MONITOR (ODM) FOR HELICOPTER GEARBOX CONDITION ASSESSMENT

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Abstract: The development of an in-line, full flow oil debris sensor system for the engine nose gearbox of a military helicopter is described. The sensor is designed as a direct one-for-one replacement of an existing magnetic chip detector, located in the scavenge oil line of the gearbox. The sensor is based on an inductive measurement technique which enables the system to detect, count and classify wear metal particles by size and type (ferromagnetic or non-ferromagnetic) with a detection efficiency of close to 100% above the minimum particle size threshold of approximately 175 microns. The design requirements, principle of operation, mechanical design features and electronic design features of the sensor are discussed. The performance /characteristics of the sensor system, as measured during development testing, are also presented.

Introduction: The mechanical components of a helicopter gearbox operate under severe conditions of load, speed and temperature. Under these conditions, component damage can progress very rapidly from the point of an initial flaw to component failure, sometimes in a matter of only a few hours of operation.

Continuous monitoring is therefore required to detect the onset of failure and provide for safe shutdown of the gearbox. Magnetic chip detectors placed in the return oil flow from the gearbox traditionally have been used for this purpose. These devices, rely on the oil-borne wear debris particles to make contact with the sensing element and remain trapped by its magnetic field. In conventional usage, the detection efficiency of a chip detector is quite poor. Moreover, chip detectors are incapable of detecting non-ferrous wear metal particles and are prone to false alarms due to the build up of fine ferrous debris. In recent years, the manufacturers of chip detection systems have introduced "fuzz-busting" electronic circuitry to address this latter deficiency; but the effectiveness of these systems is still considered to be poor by most operators.

The Oil Debris Monitor (ODM), developed jointly by BFGoodrich Aerospace and GasTOPS, overcomes the limitations of conventional chip detection systems using an advanced, full-flow, inductive sensing technology capable of continuously monitoring wear metal particles (both ferromagnetic and non-ferromagnetic) in pressurized oil lines with a detection efficiency of 100%.

In 1996, BFGoodrich and GasTOPS undertook the development of an ODM system for McDonnell Douglas Helicopter Systems in response to McDonnell Douglas' requirement for a more effective oil debris monitoring capability for the engine nose gearbox of the AH-64 helicopter. A pre-production version of this system was provided to McDonnell Douglas for performance verification testing on a ground-based gearbox test rig. An in-service evaluation of the system on an operational AH-64 is presently in progress.

This paper summarizes the design requirements of the AH-64 ODM system. The principles of operation of the ODM are described and a brief description of the mechanical and electronic design features of the AH-64 ODM are provided. Sensor performance data obtained from controlled failure progression tests are presented. The results of system performance verification tests conducted by McDonnell Douglas are also presented.

System Design Requirements: The existing chip detector is installed in a port at the front end of the nose gearbox housing, near the bottom of the oil sump (Figure 1). The detector inserts into the flow path at the point where the oil pump draws oil from the sump. The oil is drawn over the sensing head of the chip detector at a rate of roughly 3 gpm, through a coarse mesh screen (which captures larger chips) and into an oil pump inlet cavity, cast within the outer wall of the gearbox housing.

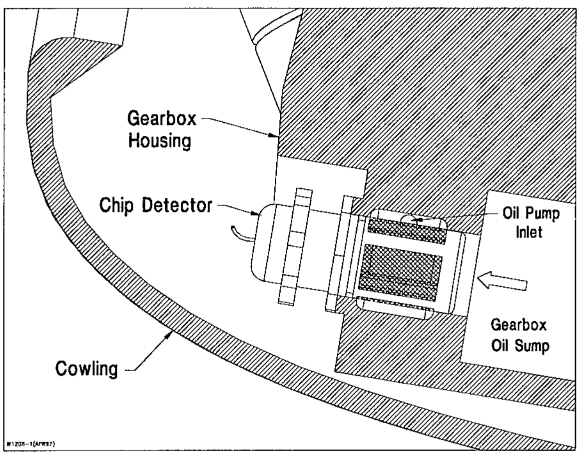

Figure 1 - Existing Chip Detector Installation

The basic design requirement of the ODM system is to replace, on a one-for-one basis, the existing chip detector. Hence, the ODM sensor is designed to be installed in the chip detector port, without modification of the gearbox housing. Additional sensor design requirements include:

- operation with oil temperatures up to 285°F
- operation with vibration levels up to 6 g's from 15 to 2000 hz
- ambient air temperature up to 140°F
- no interference with the aircraft cowling which surrounds the nose gearbox
- minimum weight increase

The electronic control unit for the sensor is located remotely in an equipment bay with cabling run from that point to each of the sensor locations (left and right hand gearboxes). As well, the control unit supports a cockpit indicator to indicate warning and alarm conditions assessed based upon the amount of debris counted by the sensors.

System Operation: The ODM is through flow device which installs in the gearbox oil supply line and allows the entire oil flow to pass without obstruction. The sensor incorporates a magnetic coil assembly which is capable of detecting and categorizing wear metal particles by size and type (ferromagnetic and conducting non-ferromagnetic). The minimum detectable particle sizes are determined primarily by the inner diameter of the coil assembly and the operating environment (temperature, vibration, EMI etc.) of the sensor. For the AH-64 application, these minimum sizes are approximately 175 microns for ferrous particles and 350 microns for non-ferrous particles.

The magnetic coil assembly consists of three coils which surround a magnetically inert section of tubing. The two outside field coils are driven by a high frequency alternating current source such that their respective fields are nominally opposed or cancel each other at a point inside the tube and just under the center sense coil. Disturbance of the magnetic fields caused by the passage of a particle results in a characteristic sense coil voltage as shown in Figure 2. The amplitude and phase of the output signature is used to identify the size and type of particle. The amplitude of the signal is proportional to the mass of the particle for ferromagnetic materials and to the surface area of the particle for non-ferromagnetic materials. The phase of the signal for non-ferromagnetic particles is opposite to that of ferromagnetic particles, allowing a distinction to be made between the two types of wear metal materials.

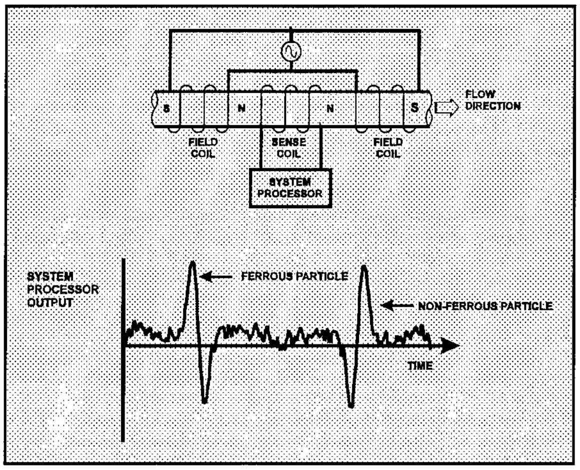

Figure 2: ODM System Operation

Odm Sensor Design: The ODM sensor design is based upon the use of an aluminum cast housing that incorporates the flow path for the oil, the support for the sensor coils and a housing for the on-sensor electronics. The design of this casting requires careful consideration to include all of these features in the confined space that is available between the gearbox and its cowling. A schematic of the sensor is shown in Figure 3.

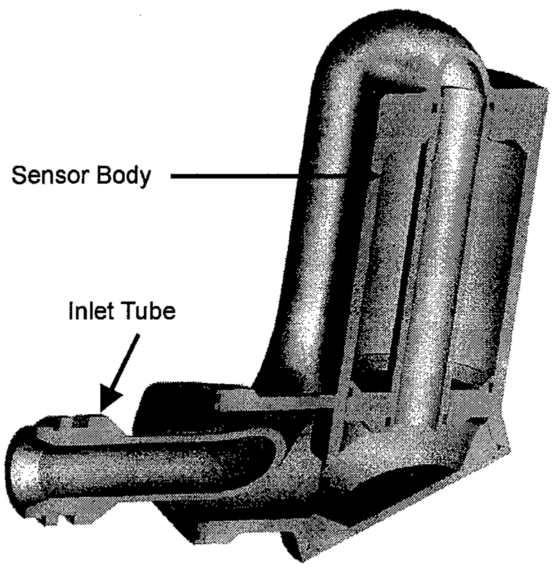

Figure 3: ODM Sensor Design

The oil enters the sensor at the inlet spigot which protrudes into the gearbox housing and seals the pump inlet cavity from the rest of the sump. This ensures that all of the oil flows through the sensor and maximizes the probability of debris detection. The oil flows through the inlet tube and around the outside of the sensor, in a cast passageway, and then into the body of the sensor where the sensing coils are located. To exit the sensor, the oil dumps into a cavity at the bottom of the sensor where it flows through an annulus around the inlet tube, and back into the pump inlet cavity in the gearbox housing. The flow path is designed to minimize pressure losses through sensor to the extent possible.

The on-sensor electronics requires special attention to allow the sensor to operate in a high temperature environment. The electronics consists of a single circuit board which is installed in an aluminum housing bolted to the side of the sensor housing. Because of the low level of the signals transmitted between the coils and the electronics, it is necessary to minimize the distance between the coils and the circuit board. At the same time this results in the circuit being closer to the oil flow which is the primary source of heat flow to the electronics.

The electronics are designed to be air cooled, using airflow that is drawn over the gearbox during operation. To maximize the cooling, the hotter components of the circuit are placed in close proximity to the outer wall of the electronics housing and a thermally conductive potting material is used to bond the circuit to the housing. On the other side of the board, an insulating potting material is used to minimize the conduction of heat from the oil to the board. This design results in the sensor being able to operate in oil at 285 F with the electronics being maintained below 200 F with only moderate air flow over the sensor.

The AH-64 ODM sensor is shown in Figure 4.

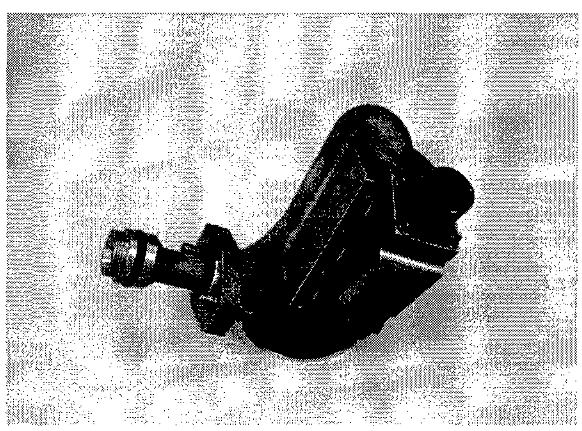

Figure 4: AH-64 ODM Sensor

Electronics Design: The particles of interest in diagnosing machinery problems are extremely small and therefore produce microvolt level signals as they pass through the ODM sensor. To reduce the complexity and cost of the cabling required between the sensor and controller, some of the electronics were built into the AH-64 ODM sensor itself as described above. This provided for a much simpler and more flexible installation suitable for a retrofit application, while maintaining sensitivity and tolerance to electromagnetic interference.

The on-sensor electronics regulate the input power to eliminate any external noise sources, generate signals necessary to energize the sensor, and process and amplify the sensor output to extract particle signature waveforms. These waveforms are transmitted back to a controller box through the same cable that powers the sensor.

The controller box (shown in Figure 5) contains a powerful TMS320 Digital Signal Processor (DSP) capable of simultaneously processing signals from four ODM sensors. The controller can be expanded to handle up to eight sensors by adding a second DSP board. The DSP continuously performs phase adjustment, filtering, and signature detection algorithms on all four channels. Any detected particles are sized, counted, and logged to an internal FLASH non-volatile memory. The DSP also calculates the estimated total accumulated mass for each sensor channel. External warning and alarm indicators are actuated based upon pre-determined mass limits. Data can be downloaded into a laptop computer on the ground to allow for analysis of the information collected.

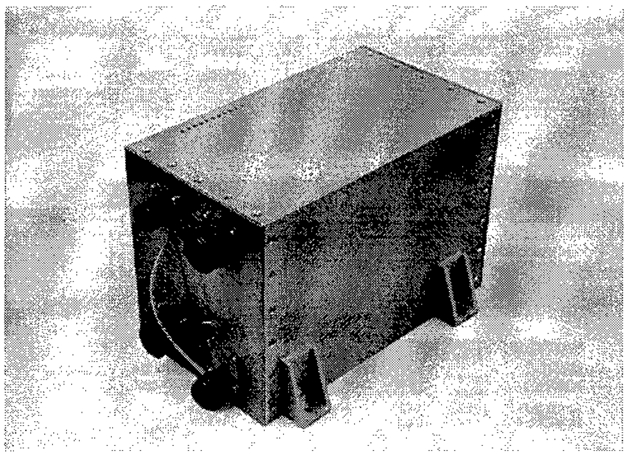

Figure 5: ODM Controller

The controller also performs periodic Built-In-Test cycles on the sensors. These tests are performed by injecting known signals into the system at the sensor itself and at the input to the controller box. This provides for a completed end-to-end test of the system as well as fault isolation.

Failure Progression Tests: In order to establish reliable criterion for warning, alarm or shutdown conditions based on the ODM output readings, a test program has been undertaken to investigate the failure of oil-wetted aircraft components. The goal of this program is to quantify the debris released from these components during failure and to evaluate the capability of the ODM to monitor failure progression.

To-date, tests have been conducted on a series of small diameter rolling element bearings as well as single tests on larger diameter bearings of conventional and hybrid designs. The results of these tests have been presented in previous publications [1, 2]. A summary of the test results are presented below.

Small Scale Bearing Tests: A large number of steel bearings (over 40 in total) have been run to failure in a test rig specially designed and instrumented for small scale (2 inch diameter) ball and roller bearings tests, as shown in Figure 6. The rig incorporates a fine mesh screen which captures the debris released during each failure for subsequent comparison to the ODM readings.

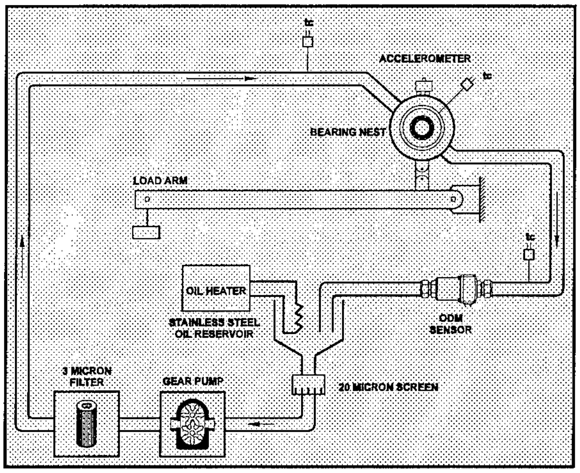

Figure 6: Bearing Test Rig

As illustrated in Figure 7, the sensor measurements indicate that large numbers of wear metal particles within the detectable size range of the sensor are released; starting with the first spall, continuing as the bearing is kept in operation and increasing in rate as damage reaches an advanced state.

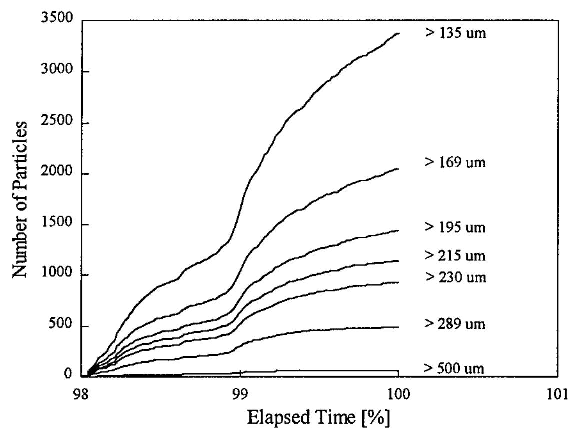

Figure 7: Small Diameter Bearing Test Results

Full Scale Bearing Test: A single test has been conducted by Pratt and Whitney on a large diameter thrust bearing from an aircraft engine application. The bearing material was steel and failure was initiated by intentionally damaging each of the functional surfaces of the bearing (inner race, outer race and balls) using 0.025 inch diameter indents. Figure 8 shows the number of particles generated above each of the ferrous particle thresholds used for the test. As indicated, the sensor detected the initial spall and counted significant numbers of wear metal particles greater than 200 microns through the failure. In total, over 150,000 ferrous particles greater than 200 microns and more than 25,000 particles larger than 700 microns were counted. Also of note was the rapid increase in the rate of particles counted during the latter portion of the test.

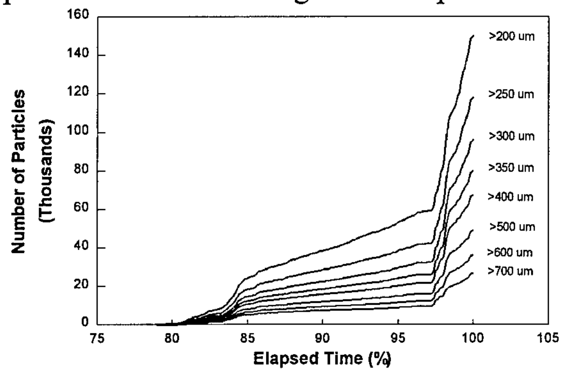

Figure 8: Large-Scale Bearing Test Results

Hybrid Bearing Test: A single test has also been conducted on an advanced technology hybrid bearing for aircraft engine application. Failure of this bearing, which incorporated ceramic balls and steel races, was initiated by a series of 0.02 inch diameter stress concentration pits created on the inner race of the bearing. Figure 9 shows the number of ferrous particles generated above each of the size thresholds used for the test. Once again, over the course of the test a large number of wear metal particles were counted by the sensor (over 7,000 particles greater than 200 microns and over 100 particles greater than 700 microns). As in the case of the large scale bearing test, a significant increase in the rate of particles counted during the latter stages of the failure was evident.

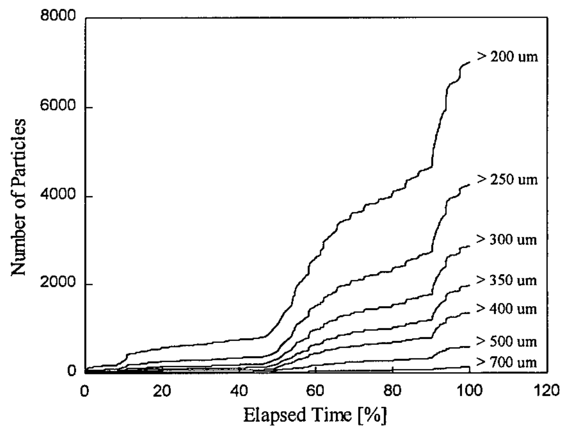

Figure 9: Hybrid Bearing Test Results

AH-64 Gearbox Rig Tests: Further testing of the AH-64 ODM system was conducted using a nose gearbox test rig located at the McDonnell Douglas facility in Phoenix, AZ. These tests were designed to verify the operation of the system in a simulated operational environment. The tests encompassed both the speed and load ranges that cover the operational envelop of the AH-64 helicopter in static as well as dynamic conditions.

In addition to the operational tests, tests were conducted to evaluate the effectiveness of particle detection of the ODM system. This was achieved by "seeding" the gearbox with random samples of metallic particles through the gearbox breather port. The gearbox, with sensor installed, was run up to speed and load and the mass of particles mass detected by the system was noted. The gearbox was then shut down, the oil filter removed, cut apart and the debris ultrasonically extracted from the filter element. The total mass detected by the ODM was 67 mg versus 28 mg recovered from the filter itself. It is noted that the filter housing attached to the gearbox contained a significant number of metallic particles once the filter was removed; all of which must have passed through the ODM sensor but did not become lodged in the filter. It was not practical to extract these particles for weighing.

It was concluded by deductive inspection that the sum of the particles extracted from the filter plus the particles in the housing was likely close to the total mass detected by the sensor.

Summary: An in-line Oil Debris Monitor (ODM) has been successfully developed for the engine nose gearbox of the AH-64 helicopter. The ODM, designed as a direct on-for-one replacement of the existing magnetic chip detector system, is capable of reliably detecting both ferrous and non-ferrous wear metal particles under full flow conditions. The system has undergone pre-flight performance verification testing at McDonnell Douglas Helicopter Systems and is currently being evaluated on an operational AH-64.

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